A PROCESS FOR EVALUATING THE BENEFITS OF NEAR-INFRARED REFLECTIVE ROOF COATINGS USED ON ASPHALT SHINGLE ROOFS

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A PROCESS FOR EVALUATING THE BENEFITS OF NEAR-INFRARED REFLECTIVE ROOF COATINGS USED ON ASPHALT SHINGLE ROOFS

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In loving memory of William H. Powers (1922-2010)

Also to Catherine J. Powers.

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LIST OF SYMBOLS AND ABBREVIATIONS

ARMA	Asphalt Roofing Manufacturers Association
ASV	Above Sheathing Ventilation
CRCM	Cool Roof Color Materials
NRCA	National Roofing Contractors Association
OSB	Oriented Strand Board
BUR	Built-up Roof Membrane
VOC	Volatile Organic Compound
IECC	International Energy Conservation Code
TRNSYS	Transient Systems Simulation Program
S/V	Surface Area to Volume Ratio
CRRC	Cool Roof Rating Council
NIR	Near-Infrared Spectrum
ε	Emissivity
G	Irradiation
EPS	Expanded Polystyrene Foam

μm	Micrometer

SUMMARY

One of the most important components of any building is the roof. It protects the interior of the building against the elements of weather and insulates the building against extremes of heat and cold. As the part of the building that is most exposed to outside conditions, the roof endures the most intense amount of solar radiation. At higher roof temperatures, roofing materials begin to deteriorate which leads to increased roof maintenance costs.

Reflective roof coatings keep the roof cooler by minimizing solar absorption and maximizing thermal emission. Keeping the surface of the roof cooler allows less heat to be conducted into the interior of the building which reduces the cooling load in air-conditioned buildings and improve comfort conditions in non-air conditioned buildings. A number of cool white materials, compatible with most roofing products, with exception of asphalt shingles, are available on the market. To appeal to homeowners, special cool “color” products have been developed to match the dark colors of conventional residential roofs but are highly reflective in the invisible near-infrared (NIR) spectrum. Although many studies highlight the benefits of cool white coatings on roof membranes of low-slope roofs, knowledge of NIR reflective coatings on asphalt shingles of steep slope roofs remains limited.

The intent of this exploratory study is to present a process that can be used to evaluate the perceived and actual benefits of NIR coatings field-applied to asphalt shingles on single-family houses. The proposed process can be applied to a large sample of homes and occupants in a future study. A questionnaire was designed to attempt to evaluate occupants’ perceived benefits in regards to their indoor environment and occupant satisfaction following applications of NIR coatings. Along with subjective data collection, a field-experiment was developed to objectively compare the thermal performance of an NIR reflective field-coated asphalt shingle roof system with that of a conventional asphalt shingle roof system.

Questionnaire results indicated that occupants did not perceive any significant changes to their indoor environment but were satisfied overall with the application and appearance of the roof coating. Additionally, 50% of occupants stated that their monthly energy costs somewhat decreased after the application. Interestingly, 63% of respondents experienced some form of roof leak following the coating application. Among those who experienced roof leaks, 100% of the roofs were 10 years or older. Field results showed that the coated roof surface was 2 to 5°F cooler than the uncoated roof surface at midafternoon. Statistical testing for correlation between coated roof surface temperature and external conditions revealed that relative humidity was negatively correlated with coated roof temperature, while solar altitude angle was positively correlated with coated roof temperature. Multiple linear regression analysis was used to develop a model for predicting the surface temperature of the coated asphalt shingle roofs from the ambient temperature, sky conditions, dew point temperature, relative humidity, solar altitude and azimuth angle.

CHAPTER 1

INTRODUCTION

As a major component of a building, the roof is the first line of defense against the elements. It protects the interior of the building from rain, snow, wind, and sun. The roof also serves a major role in the thermal envelope by insulating the building from extremes of heat and cold. As the front-line of defense, the roof is subject to the most intense solar radiation of any other component of a building. Roof surface temperature can fluctuate from below freezing to near boiling all in one day (Finishing the Roof, 2002). At higher roof temperatures, the deterioration of roofing materials starts and leads to increased roof maintenance costs, and high levels of roofing waste directed to landfills.

Roof coatings have long been used on commercial buildings as an economical way to extend the life of roof coverings and to save energy. Roof coatings, also known as *cool roofs*, are characterized by materials having high solar reflectance and high thermal emittance. Cool roofs save energy by keeping the surface of the roof cooler allowing less heat to be conducted into the interior of the building which reduces the cooling load in air-conditioned buildings. In buildings without air-conditioning, cool roofs improve interior comfort. In dense urban areas, there are indirect benefits as a result of the reduction in air temperature. Cool roofs can help mitigate urban heat island effect and air pollution. A number of white and light colored cool roofs are available on the market. In hopes of appealing to more homeowners, new cool colored products have been developed to match the darker colors of conventional residential roofs but are highly reflective. The performance of cool roofs has been investigated in earlier studies. Many studies on the performance of cool roofs have been conducted by means of software simulations with limited real building applications. Secondly, most studies have focused on the performance of cool coatings on flat roofs. Flat roofs are considered ideal candidates because they absorb sun energy at higher levels than pitched roofs. There is much debate in the roofing industry about the application and effects of field-applied roof coatings on the steep-sloped roofs of houses that typically have asphalt shingles. The Asphalt Roofing Manufactures Association (ARMA) and the National Roofing Contractors Association (NRCA) both suggest that asphalt shingle roofs are not designed to accept or require field-applied surfacing. There are some concerns regarding the reduced permeability once a roof coating is applied, the aggressive cleaning of the shingles that is done before application and whether or not it meets fire and wind resistance code amongst other issues. Coatings manufacturers and contractors, however, say coatings can be successfully applied to asphalt-shingle roofs, extending the roof service life.

1.1 Roof Classification

Roofs are classified according to their steepness or slope. Slope is expressed as a ratio of the (vertical) rise to the (horizontal) run of the roof. In the United States, slope is expressed in inches of rise per 12-inch run. Roof materials are also grouped according to the roof slope: those that can be used on *low-sloped roofs* and those that can be used on *steep roofs*. The National Roofing Contractors Association defines a steep roof as a roof with a slope of 4:12 or greater. Likewise, a roof with a slope of less than 4:12 is considered a low-sloped roof. A steep roof has the advantage of being able to quickly drain water, with little risk of wind and gravity pushing or pulling water through the roofing material. Because of this, steep roofs can be covered with roofing materials that are fabricated and applied in small overlapping units such as shingles or tiles. The small units are easy to handle, install, and repair. The effects of thermal expansion and contraction, and movements of the structure that supports the roof, are minimized by the ability of the small units to move with respect to one another. Additionally, water vapor is able to vent out from the interior of the building through the loose joints in the roofing material (Finishing the Roof, 2002). One concern of applying a roof coating, is that it would reduce the permeability of these small units – i.e. shingles, tiles. Shingles are designed to shed water, not to be water proof. In contrast, low-slope roofs drain water from itself relatively slowly. As a result, small, individual units would not be a suitable roofing material for this roof type. To prevent water penetration, low-slope roofs must be entirely continuous and are referred to as membranes. There are three general types of membranes: the built-up roof membrane (BUR), the single-ply roof membrane, and the fluid-applied roof membrane.

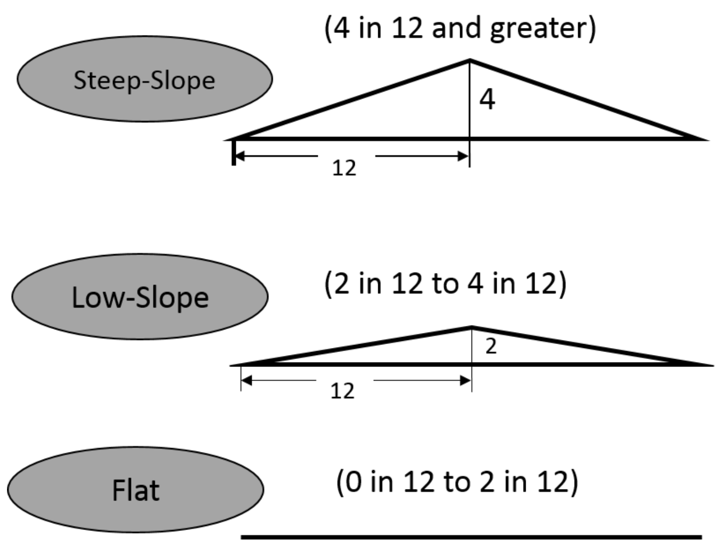

Figure 1: Roof Slope

1.2 Defining Cool Roofs

Roofs that stay cool in the sun by minimizing solar absorption[1] and maximizing thermal emission are known as "cool roofs" (Akbari & Levinson, 2008). They are characterized by a high solar reflectance (or high ability to reflect solar radiation incident on the material) and thermal emissivity (or high ability to radiate heat in the infrared wavelengths). The high reflectivity is due to pigments characterized by a high reflectance in the infrared portion of the solar spectrum, maintaining the typical profile in the visible spectrum. High emissivity allows the material to stay cool during the night, radiating towards the sky the heat absorbed during the day (Carnielo, Fanchiotti, & Zinzi, 2011). Cool roofs can be made of highly reflective type paint, a sheet covering, or highly reflective tiles or shingles. Simulation studies suggest that cool roof technology can help mitigate the urban heat island effect when implemented on a larger scale in urban areas. Earlier studies have shown that savings are greatest for buildings located in hot climates with long cooling seasons and short heating seasons (Akbari, 1998).

A cooler roof reduces the flow of heat from the roof into the building and ultimately onto the occupants of the building. It also reduces peak electricity demand in mid to late afternoon, the warmest part of the day. A bright white, smooth surface can reflect about 85% of incident sunlight and emit thermal radiation with 90% efficiency. This is the coolest type of roofing surface; however, most North American homeowners typically select nonwhite products for pitched roofs.

1.3 Cool Color Technology

About half of all sunlight arrives in the invisible near-infrared (NIR) spectrum (0.7-2.5μm). Figure 2 illustrates the Electromagnetic Radiation Spectrum. Standard light colored surfaces strongly reflect both visible and near-infrared sunlight, while standard dark colored surfaces reflect modestly in both spectra. Special dark and medium-colored surfaces strongly reflect NIR sunlight are called “cool colors.” Reflectance in the NIR spectrum is maximized by coloring a topcoat with pigments that weakly absorb and (optionally) strongly backscatter NIR radiation, and by adding an NIR reflective basecoat (i.e. titanium dioxide rutile white) if both the topcoat and substrate weakly reflect NIR radiation (Levinson, et al., 2007). The solar reflectance of a shingle is greatly determined by the solar reflectance of its granules which cover more than 97% of its surface (Akbari, Levinson, Miller, & Berdahl, 2005). Levinson, et al. (2007) found that granule-surfaced asphalt shingles achieved NIR reflectances as high as 0.45 when the granules were covered with a white base coat and a cool color topcoat. In contrast, a conventional asphalt shingle has a reflectance of only about 0.06. Therefore, improving the solar reflectance of asphalt shingles could have a significant impact on the electrical energy used for residential cooling.

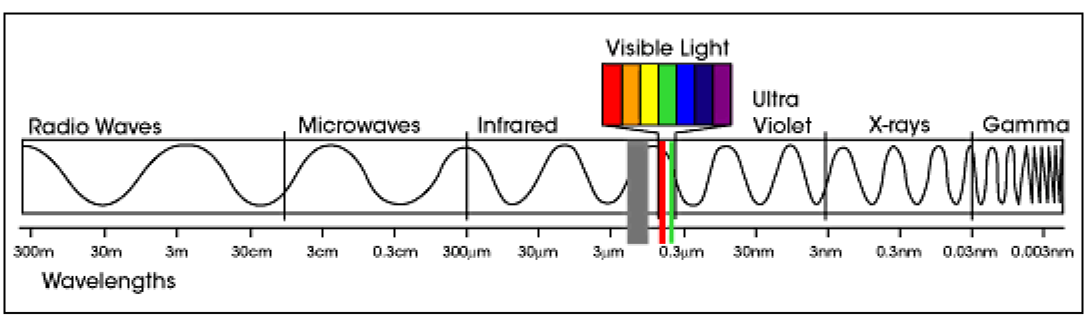

Figure 2: Electromagnetic Radiation Spectrum (NASA's Earth Observatory)

1.4 Roof Coating Materials

Coatings can be categorized by application: field-applied or factory-applied. This paper focuses on field-applied coatings. There are two main product types of roof coatings: 1) elastomeric-based and 2) bituminous-based coatings. The selection of product type will depend on the kind and purpose of the building (Report 2004). Elastomeric-based coatings are made of flexible materials and include acrylics, Hypalon, neoprene, silicone, and urethane and hybrid materials. This product is compatible with most types of roofing system but most commonly used on single-ply, spray applied polyurethane foam, and metal roofing systems. Elastomeric-based coatings can reflect up to 90% total thermal radiation (Romen L, et al, 2005). Their high reflective properties reduce daily cooling loads and acts as an insulator. They also have strong rust inhibitive pigments and fungicides which help prevent premature degradation. Generally, elastomeric coatings are easy to use, clean-up, non-toxic and VOC (Volatile Organic Compound) compliant water based coating. Bituminous-coatings contain asphalt or tar and are manufactured to be compatible with asphalt or coal-tar BUR, as well as metal roofing. The coating builds a waterproof and flexible protective coat that is near solid when under ambient temperatures (Bituminous Coating, n.d.).

1.5 Roof Coating Application Procedure

Before a coating is applied, the roof is examined carefully for any signs of wear, cracks, tears, debris, or evidence of ponded water. Any serious roofing problems should be addressed. The next step is to thoroughly clean the roof surface in preparation of coating. Typically a pressure washer is used to remove all dirt and debris. The roof is allowed to dry for an appropriate amount time. Once the roof is dry, it is inspected for a second time for any visible damages.

Weather conditions must be suitable during and immediately after application for successful coating adhesion. Generally coating manufactures describe ideal weather conditions as temperatures greater than 50°F and no precipitation for a period necessary to achieve moisture-resistant cure levels (Rupar, 2010). The coating can be applied with a roller or an airless paint sprayer. A paint sprayer is recommended for coating shingle roof systems. Each coat should be allowed to dry for four to six hours before applying a second coat. Generally, two to three coats are considered sufficient to effectively cover the roof.

Figure 3: Pressure washing the roof to clear the roof of dirt and debris.

Figure 4: Application of roof coating with paint sprayer.

1.6 Performance & Testing Standards

The two main characteristics that are used to rate the performance of a coated roof are solar reflectance and thermal emittance. Both metrics are rated on a scale from 0 to 1. Solar reflectance helps prevent degradation of the roof from sunlight. To obtain Energy Star Certification from the US Environmental Protection Agency, steep-sloped roofs must exhibit a minimum initial solar reflectance of at least 0.25 and a reflectance of 0.15 or greater after three years of weathering (Energy Star, 2015). In contrast, conventional asphalt roof have a reflectivity of between 0.06 and 0.26 (Fact sheet for low slope roofs, 2011). There are two standard test methods available for measuring roof coatings' solar reflectance. Roof coatings' solar reflectance may be measured according to ASTM C1549, "Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer" or ASTM E1918, "Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-slope Surfaces in the Field. Thermal emittance is defined as the coatings ability to radiate thermal heat back into the atmosphere. The three standard test methods available for measuring roof coatings' thermal emittance include: 1) ASTM E408, "Standard Test Methods for Total

Normal Emittance of Surfaces Inspection-Meter Techniques," or ASTM C1372, "Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissonmeters." Other important performance metrics include: low temperature flexibility, dirt pickup resistance, resistance to ponded water, and adhesion to roof substrate. Using a coating that remains flexible at low temperatures without becoming brittle or cracking is critical because roof systems are dynamic environments that are constantly contracting and expanding. How well the coating will adhere to the roof substrate is equally important in the selection process.

The amount of flexibility of a coating can be tested by conducting a percent elongation testing. A machine called an Instron Tester grips the sample between two jaws and the machine pulls and stretches the sample. The amount of stretching is measured at low, high, and room temperature. Roof products typically undergo degradation from oxidation reactions that result from combinations of thermal degradation and photodegradation – due to ultraviolet (UV) light. The durability of coatings can also be tested through accelerated weathering. A machine called a Weather-Ometer ages the coating for several thousand hours in which afterwards the elongation is retested. In regards to reflectivity, this can be measured using an infrared thermometer to measure surface temperature. Generally lighter colors will reflect more heat with bright white providing the highest level of reflectivity.

1.7 Concerns in the Roofing Industry

Asphalt shingle manufactures disagree with coating manufactures and contractors regarding the use field-applied, solar reflective coatings on asphalt shingles. Although contractors and coating manufactures state that coatings can be successfully applied to certain asphalt shingle roofs, there is limited evidence to support their claims. There are several concerns that field application of coatings over asphalt shingle roof systems will have negative consequences. The Asphalt Roofing Manufacturers Association (ARMA) released a technical bulletin strongly advising against the application any type of field-applied coating over installed asphalt shingle. ARMA Technical Bulletin No 227 states that problems have been reported after asphalt shingle roofs were coated including shrinking of the coating which may result in curling and/or cupping of the shingles or loosening of the granule surfacing of the shingles. Another concern is that coatings marketed for application on asphalt shingle roof systems often do not possess fire-resistance ratings. Roof coatings rated for fire resistance as part of low-slope bituminous roof systems are not suitable for application over asphalt shingle roof systems. Additionally, local building codes may prohibit field applying coatings, and manufactures' warranties may exclude coverage for damage to their products caused by coating or painting.

In some cases, litigation has ensued due to unwanted effects of field-coated asphalt shingles. According to reports by *Sun Sentinel*, Florida Power & Light (FPL) reimbursed contractors to paint over 4,000 asphalt-shingle roofs white to reflect sunlight. For several years the utility company provided rebates to its customers for the application of white coatings as part of its initiative to reduce electricity use and costs. Roughly 12 of its customers complained that the roofs started to deteriorate or leak after they were coated. Five customers filed a lawsuit against the utility company and the contractor who performed the work. In response, FPL stated that customers make arrangements with independent contractors who are responsible for the work and for complying with building codes, while they only provide the incentives to help with the costs.

Because of the many types and formulations of roof coatings and possible risks, ARMA advises homeowners to obtain approval from the shingle manufacturer and to check with local building department to determine if the particular coating application is allowed.

1.8 Research Objectives

The research seeks to present a mix-method approach for evaluating the benefits of NIR reflective roof coatings used on asphalt shingle roofs of single family's houses. To improve the evaluation of their benefits, both qualitative and quantitative data collection is proposed. The paper consists of a literature review of previous field and computer simulated studies, along with a discussion of the questionnaire and field-experiment design. Analysis of the survey results and the field-experiment is discussed along with problems faced during the data collection process. The specific objectives of this study are as follows:

- To present a process for evaluating occupants' perceived benefits of NIR reflective coatings field-applied to asphalt shingle roofs
- To present a methodology for comparing the thermal behavior of a NIR field-coated roof with that of a conventional roof
- To establish groundwork for further research of the use of NIR reflective coatings on houses

CHAPTER 2

LITERATURE REVIEW

2.1 Cool Roof Simulation Studies

The performance and effects of cool roofs has been investigated in numerous studies by way of computer simulations under different climatic conditions. Many studies have focused on flat roof buildings with limited knowledge on their performance on steep-slope or asphalt shingle roof systems.

Synnefa, Santamouris, and Akbari (2007) evaluated the potential energy savings and the impact of thermal comfort from the use of cool roof coatings for residential buildings in various climate conditions where the heating penalty was less important than the cooling load reduction. Using TRYNSYS thermal simulation software, they estimated the effect of cool and cool colored materials on the residential energy load in different climatic conditions, including Mediterranean, humid continental, subtropical arid, and desert conditions. They performed the analysis on a non-directional, single story, flat roof house, with a roof area $100m^2$. The roof had a base solar reflectance equal to 0.2. The results showed that increasing roof solar reflectance by 0.65 reduces cooling loads by 8-48 $\boldsymbol{kWh/m^2}$ or 18-93% and peak cooling demand in air-conditioned buildings by 11-27%. The indoor thermal comfort conditions were improved by decreasing the hours of discomfort by 9-100% and the maximum temperature in non-air-conditioned residential buildings by 1.2-3.3℃. The results also showed that increasing solar reflectance by 0.65 from 0.2, can achieve savings that vary between 10-27% depending on the specific climate conditions. Synnefa, et al. found that these reductions were more important for poorly or non-insulated buildings. Increasing solar reflectance of a roof is typically more beneficial in hot climates where cooling load dominated most of the year. A parametric analysis showed that the two factors affecting the energy savings from using cool coatings were the climate and U-value of the roof.

Zinzi and Agnoli (2011) analyzed how cool roofs can improve energy performance and thermal comfort of residential buildings in different climates of the Mediterranean region. They performed thermal analyses on 2-story row houses and 1-story detached single family houses, with and without insulation. Using Design Builder, which uses Energy Plus, a comparison was conducted for different roof solutions including a conventional roof, white cool roof, metallic reflective coating, and green roof. Results showed that the best performing roof solution depended on climate conditions and house typology. Cool roofs were found to be very effective for the cooling and energy savings and the most effective solutions for the central and southern areas of the Mediterranean basin. Their results also showed that houses that are not insulated may have excessive increase in heating demand but very low cooling energy demand. Metallic cool roofs with low emittance performed worse than cools roofs because of reduced radiative losses at night, but still outperformed conventional roofs. Metallic cool roofs also experienced limited heating penalties in comparison to cool roofs, suggesting metallic cool roofs may be an acceptable solution for cooler areas.

2.1.2 The effect of solar reflectance on moisture behavior

Ahrab and Akbari (2012) studied the effect of solar reflectance on the hygrothermal performance of roofing systems in different climate regions. Using WUFI

Pro 5.1, they simulated the performance of various roofing systems with white and dark surfaces in 13 different climate regions across North America for a period of 5 years. To evaluate the hygrothermal behavior of roofs, they considered surface temperature, total moisture content in the roofing assembly, risk of mold growth, and the moisture content of wooden materials. The results from the study showed that dark roofs always experienced lower moisture content compared to white roofs. Moisture performance of white roofs were very similar to dark roofs in hot climates. In residential buildings, white, typical roofing compositions with conventional vapor retarders experienced moisture accumulation problems in very cold cities. Using smart vapor retardor or self-drying roofs helped to decrease risk of mold accumulation. The study also showed that adding a ventilated air space along with using a smart vapor retardor eliminated the risk of moisture accumulation and lowered the risk of mold growth. Snow accumulation on the roof was showed to slightly improve the moisture behavior of roofing assembly.

2.1.3 Mitigating the urban heat island effect (UHI)

Cool roofs effectiveness in mitigating the urban heat island effect has also been studied. The Center for Integrated Solutions to Climate Challenges at Arizona State University (2014) investigated what cooling benefits can be achieved from implementing cool roofs under existing conditions and projected warming. They modeled the impact of cool roofs on near-ground air temperatures and human thermal comfort in the Phoenix metropolitan areas using ENVI-met software. The results showed that the effect of cool roofs were relatively low, reducing neighborhood air temperatures by 0.3℃ when implemented on residential homes. In a study by Georgescu (2012), they found that painting all rooftops white on a regional scale could reduce annual rainfall due to the reduction in low-level heating which removes the natural lifting mechanism required for condensation to occur.

2.2 Cool Roof Field-Studies

In a series of field experiments in Florida, Parker, Huang, Konopacki, Gartland, Sherwin, and Gu (1998) examined the impact of reflective roof coatings on air-conditioning (AC) energy use on residential buildings. The test was conducted on nine residential buildings built from 1991 to 1994. The roofs were coated white at mid-summer using a before-and-after protocol. AC electrical savings in the buildings were measured during similar pre- and post-retrofit periods and averaged 19 percent, ranging from a low of 2 percent to a high of 43 percent. Utility peak savings averaged 22 percent. Results from the test suggested that the cooling energy reductions depend on ceiling insulation level, roof solar reflectance, air duct system location, and air conditioner sizing relating to load. A complimentary thermal study of the effect of reflective roofing systems was also conducted which found ceiling heat flux reduced by up to 60 percent. However, the test results also showed degradation in solar reflectance and associated thermal performance after a year of exposure.

The relative performance of a NIR reflective tile coating against conventional, uncoated tiles was evaluated in a study by Miller, et al. (2010). In addition, they investigated the effect of enhanced above sheathing ventilation (ASV). They conducted field experiments on two pairs of single family detached homes on the campus of Fort Irwin. Two of the houses were painted with the reflective coating and two were left with their original painted surfaces. One house from each pair had their tiles laid direct-to-deck and the tiles on the other two houses were laid on double battens. Their field measures and computer predictions showed that the home without the NIR-reflective tile coating and without ASV had the greatest roof deck heat flow and the highest electrical usage. The house with both NIR tile coating and with ASV had the least deck heat flows and therefore cause the home to consume the least amount of energy. Because of the effect of the occupants, however, they were unable to determine the relative performance of the reflective coating individually.

The passive-active effect produced by cool roofs on an industrial building located in Rome, Italy was investigated by Pisello, Santamouris, and Cotana (2013). The active effect studied consisted of the cool coating's capability to decrease the suction air temperature of heat pump when the external units are located over the roof. They continuously monitored an open office in a non-insulated, 1000m^2 industrial building in the summer of 2012 before and after the cool roof application. To quantify the passive cooling benefit produced by the cool coating, they performed an analysis of the roof thermal behavior and of the indoor thermal behavior. Their main results showed that the cool roof is able to annul the suction air overheating with respect to the outdoor temperature. The cool coating also decreased the daily thermal peak of the roof external surface temperature by 10-15℃. However, during the night, the surface temperature did not highlight any evident difference between the two scenarios. The study also showed that the cool roof was able to decrease the heat gain entering the roof and the indoor air temperature of the office area by 2-4℃, even if the set-point temperature of the cooling system was kept constant for the period of the study. Because they were unable to control for the effect of the occupants, however, they could not determine the performance of the coating individually.

2.3 Long-term Performance & Weathering

Highly reflective coatings used on residential buildings in hot and dry climates have been able to achieve cooling energy savings of 10% to 70% (Bretz & Akbari, 1997). However, dirt accumulation and weathering can alter the long-term performance of the cool roof. Bretz and Akbari examined different reflective coatings at various stages of exposure to determine the extent of the effect. They found that the majority of the degradation of coatings occurred within the first year and even within the first two months of exposure. In one scenario, the roof's solar reflectance fell by 70% within the first year; however, data indicated that degradation slowed after the second year. Washing the roof with soap is effective at restoring reflectance, but it may not be cost-effective to pay someone to clean the roof only to achieve energy savings. Instead, Akbari, et al. recommend developing and identifying dirt resistant reflective coatings.

In a study by Sleiman, et al. (2011), they evaluated solar reflectance losses after three years of natural exposure reported in two separate databases: the Rated Products Directory of the US Cool Roof Rating Council (CRRC) and information reported by manufacturers to the US Environmental Protection Agency (EPA)'s ENERGY STAR rating program. The findings from the study revealed that products with high initial solar reflectance tend to lose reflectance, while those with very low initial solar reflectance tended to become more reflective as they aged. The study also found that absolute solar reflectance losses for samples of medium-to-high initial solar reflectance were 2 to 3 times greater in Florida (hot and humid) than in Arizona (hot and dry);. Losses in Ohio (temperate but polluted) were intermediate. Additionally, they found that absolute solar reflectance losses were largest for field applied coating, and smallest for factory-applied coating and metal products.

CHAPTER 3

METHODOLOGY & RESEARCH DESIGN

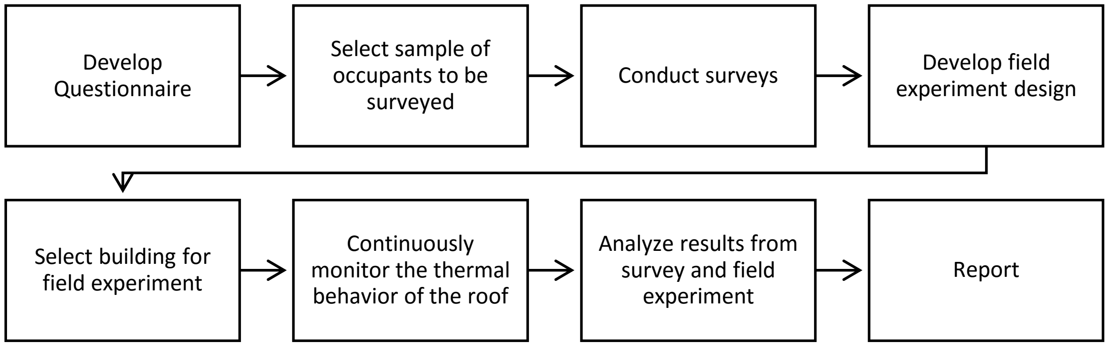

Figure 5: Research Process.

3.1 Study Area

The study focused on the city of Albany, Georgia, representing a hot and humid climate, or climate zone 3A of the IECC climate zones (Figure 6). The mean annual air temperature of Albany is 66°F, with a mean value of 83°F in July, the warmest month, and a mean of 50°F in January, the coldest month. Albany has an average annual rainfall of 51.5 inches (U.S. Climate Data, 2015). Climate conditions of the study area are reported in Table 1.

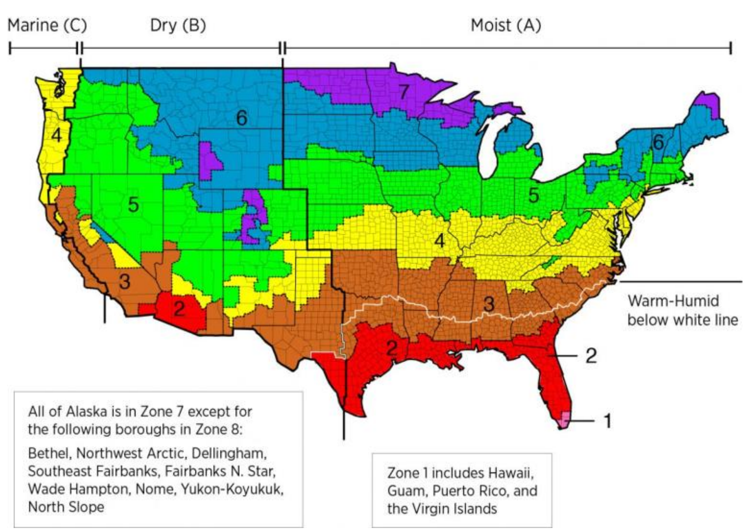

Figure 6: IECC Climate Zone Map

Table 1: Climate Conditions of Study Area.

Parameter	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$T_{\text{max-average}}$ (^{0}F)	60	64	71	78	86	91	93	92	88	80	71	62
$T_{\text{min-average}}$ (^{0}F)	36	39	45	51	61	69	72	72	66	55	45	39
Rainfall rate (in)	5.1	4.4	5.28	3.4	3.27	5	5.9	5.2	3.7	2.6	3.6	4
Rainy days (≥.03 in)	10	14	8	10	9	13	7	10	13	4	7	9

3.2 Questionnaires

Occupant's assessment of NIR reflective coatings can provide valuable insight about their performance and satisfaction levels. Questionnaires were conducted via phone during the period of December 2014 to January 2015. Consisting of 26 questions, the questionnaire was designed to collect data on occupants' perception of benefits and/or changes to their indoor environment after the applications of cool color coatings. The questionnaire included three categories: general questions, questions regarding the roof and roof coating applied, and questions regarding perceptions of the changes in indoor environment. The general questions included questions about number of bedrooms, bathrooms, floors, size of home, and years lived in the home.

Respondents were asked to give their feedback regarding perceived changes to indoor air quality, noise level, utility costs, coating appearance, and satisfaction of the roof coating. Additionally, we inquired about any occurrences of leaks and storm damage since the application as there is much concern about these issues. The entire questionnaire took approximately 15 to 20 minutes to complete. The targeted respondents were homeowners or occupants of single-family detached homes in Albany, GA. Respondents were referred by a local roofing company in Albany, Georgia that specializes in installing cool roof coatings. A total of 20 homeowners were called and asked to participate in the survey, and 14 responses were received. Of the 14 respondents, 8 received installation of cool color roofs, while the remaining 6 had not received installation of cool color roofs. Before being asked to answer the questionnaire, subjects were briefly introduced on the structure and purpose of the survey. Each home is a one-story, 2 to 3 bedroom dwelling. Eighty-six percent of the homeowners lived in houses with roofs that were 10 years or older. The percentage distribution of valid replies by age of roof is presented in Figure 7. The survey instrument used is provided in Appendix A.

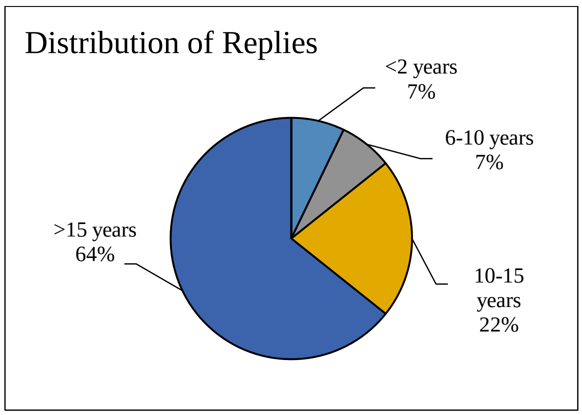

Figure 7: Percentage distribution of replies by age of roof.

3.3 Field-Experiment

Along with occupant questionnaire surveys, a field-experiment was carried out on the roof of a single-room, unoccupied, unconditioned, shed built in 2000 in Albany, Georgia to measure the thermal behavior of cool colored roof coatings on the roofing assembly. The existing roof is 14 years old and has not been replaced or repaired since the shed was built. It represents a common house typology of the region with a gable asphalt shingle roof and a 4" in 12" slope (18.4°). The roof is a non-insulated roof with a wood frame structure. The shed is 12.25 x 12.17 ft, totaling 149.04ft^2, with a volume of

$1{,}779 ft^3$. The shed faces south, being 181°S from magnetic north; the ridge is oriented east and west. Elevations of the shed are shown in Figure 8. Specifications of the shed are presented in Table 2. The color of the existing asphalt shingle was considered autumn brown. The solar reflectance of the shingle was considered to be 0.09. Thermal emittance of the shingle was considered to be 0.91.

Figure 8: Test Shed Elevations

Table 2: Building Materials

	Exterior →				**Interior**
	1	**2**	**3**	**4**	**5**
Walls	Vinyl Siding (~.42mm)	Oriented Strand Board (OSB; 7/16")	2x4 wood framing @ 16" o.c.	-	-
Roof	Asphalt Shingles	Roofing Felt	Oriented Strand Board (OSB; 7/16")	2x6 rafters and joists @ 16" o.c.	1/2" gypsum board

For the field experiment, the roof was divided in to 2 roofing assemblies of similar width of 6’2” and similar length of 15’2” on the south and north facing roofs.

Before applying the coating, the roof was pressure washed to clear it of all dirt and debris. Because of continuous rain, the coating application had to be postponed for 2 weeks to wait for dryer conditions. The roofer was directed to select the brand and color of the NIR reflective coating that closely matched the autumn brown color of the existing shingles. Using an airless spay gun, the roofer applied the equivalent of two coatings of Jasper Nutech NXT Cool Zone reflective coating (total solar reflectance of 0.331 and thermal emittance of 0.88) to module 2. Module 1 was left uncoated as the control for comparing the thermal performance of a conventional roof with that of a NIR reflective coated roof. In order to avoid heat transmission between the two modules, the path of connection was insulated with expanded polystyrene foam panel (total thickness of 2.5 inches) and positioned vertically (Figure 10).

Figure 9: South-facing Module 2 (coated with Jasper Nutech NXT Cool Zone) and Module 1 (uncoated) roof.

3.4 Instrumentation and Data Acquisition

The roofing assemblies were monitored continuously for 15 days, beginning on April 13th to April 27th, 2015. The monitoring period was during what would be considered spring season for the area. A total of 6 Elitech LCD USB temperature data-loggers were placed at the external roof surfaces and within the attic of each module to measure temperatures. The data loggers were programmed to record temperatures at 5-minute intervals. Figures 9 and 10 illustrate the location of each data logger. Ambient temperature, relative humidity, sky conditions, wind direction, and wind speed recorded at 8–minute intervals were obtained from the nearest weather station in Albany, available on an online database (NOAA's National Centers for Environmental Information, 2015). For analysis of the field measurements, temperatures were averaged over each hour interval. More than 4,480 data points were obtained and analyzed.

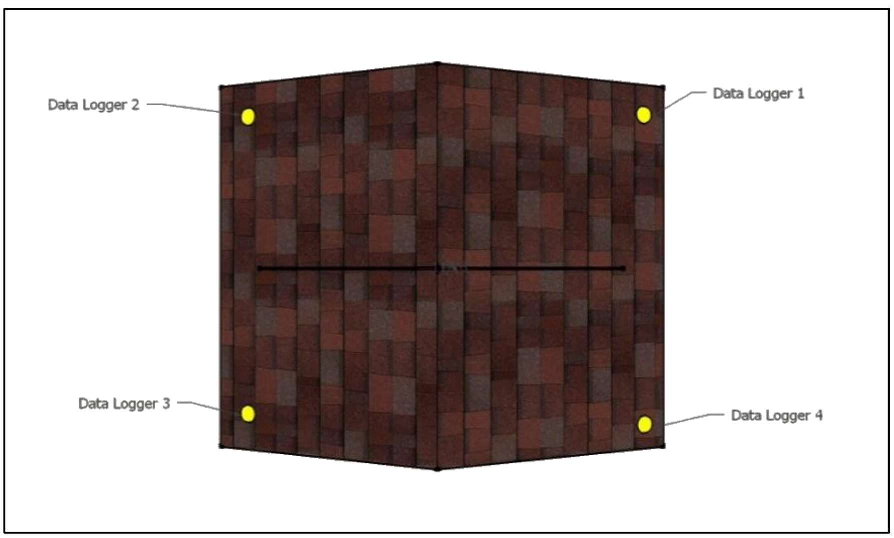

Figure 10: Top of Roof: Data Logger Locations

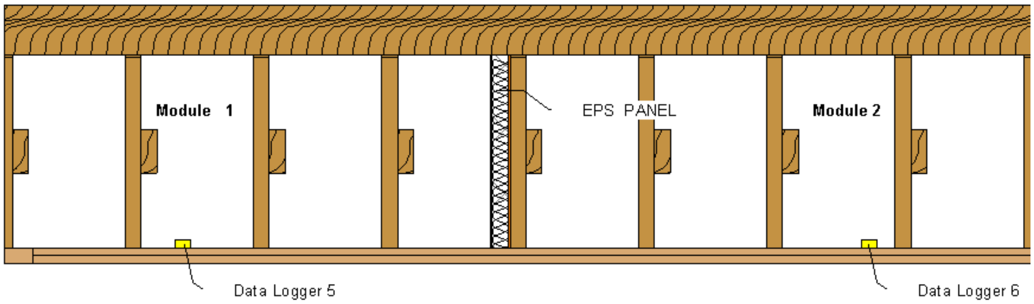

Figure 11: Roof Section: Internal Data Logger Locations

CHAPTER 4

RESULTS & DATA ANALYSIS

4.1 Survey responses

Due to the limited number of respondents available for the questionnaire, statistical tests were omitted and responses are presented with descriptive statistics.

The roof of every house had a cool color coating applied within the last 4 years. Among which, 63% of the coatings had been applied within the last 6 months. A cool "dark" color coating had been applied to half of the roofs, while a cool "light" (non-white) color coating had been applied to the other half of the roofs. All homes have central AC systems, of which 85% of occupants reported that the air ducts were not located in the attic of the homes. We inquired about the location of air ducts because previous field experiments suggested that the cooling energy savings were influenced by interactions between the duct system and the space in which it is located (Parker, et al., 1998). We also inquired about insulation in the home. Field studies have found that energy savings are more pronounced in older homes without insulation in the attic (Akbari, Levinson, Miller, & Berdahl, 2005). None of the roofs had received a reapplication of the roof coating.

4.1.1 Indoor air quality perception

Figure 11 shows the percentage distribution of responses in regards to changes in air quality. As it can be observed, 75% of occupants perceived no change in air quality within their indoor environment. One occupant responded that the air inside the home was humid.

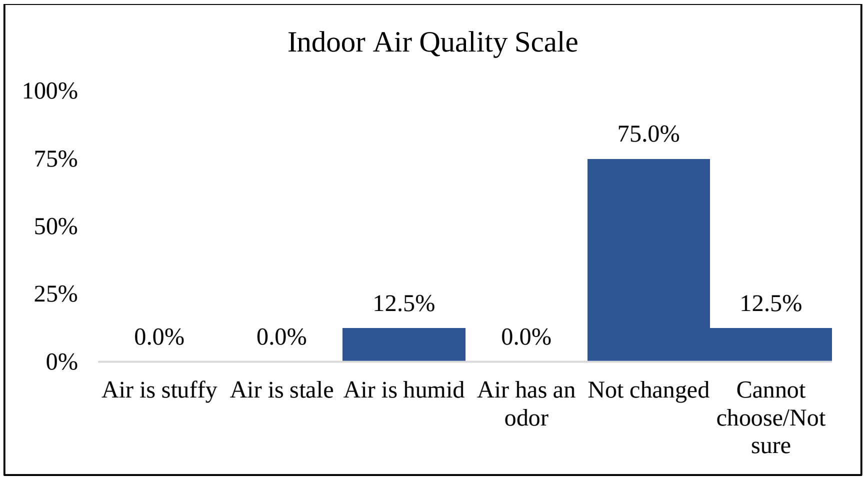

Figure 12: Indoor Air Quality Scale. Percentage distribution of replies.

4.1.2 Energy costs perceptions

NIR reflective roof coatings save energy by keeping the surface of the roof cooler, allowing less heat to be conducted into the interior of the building which reduces cooling loads. Previous studies have found that within the first year of exposure, however, coatings can lose as much as 70% of solar reflectance because of weathering and dirt accumulation (Bretz & Akbari, 1997). Additionally, Sleiman et al. found that solar reflectance loses were largest for field applied coating. Our survey results indicated that half of respondents felt they experienced somewhat of a decrease in their energy costs. Among those, 50% of the coatings had been applied within 6 months, while the other 50% of the coatings had been applied within 3 to 4 years (Figure 12).

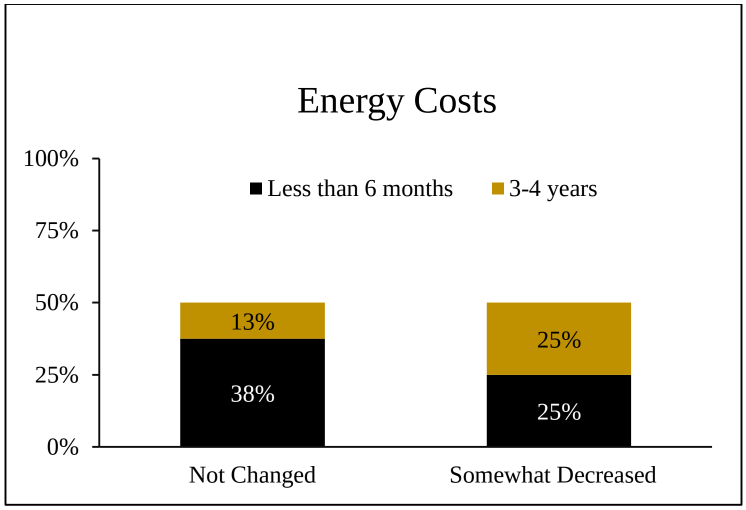

Figure 13: Energy Costs percentage distribution of replies with respect to time of coating application.

<u>4.1.3 Amount of outside noise perceptions</u>

As expected, none of the occupants perceived any changes in the amount of noise heard from outside.

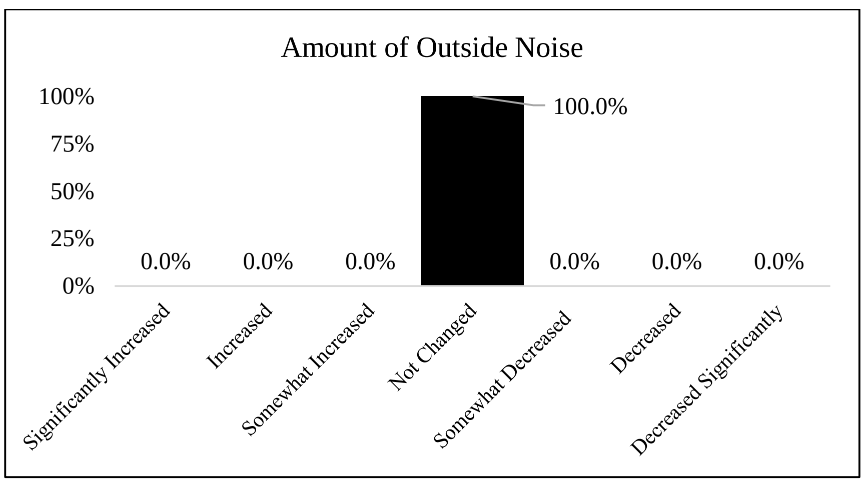

Figure 14: Amount of outside noise scale. Percentage distribution of replies.

<u>4.1.4 Roof leaks and storm damage</u>

Interestingly, 63% of respondents reported experiencing some form of roof leak after the application of the coating. Among those, 100% of the roofs were 10 years or older in age providing anecdotal evidence that coatings should not be applied to older, worn shingles. Several roof coatings for field application are marketed to homeowners as an economical way to extend the service life of the roof and delay expensive roof replacement. The leaks may have been caused by water infiltration and damage from too vigorous pressure washing that is done to clean and clear the roof from debris. Furthermore, the Asphalt Roofing Manufactures Association (ARMA) does not recommend pressure washing asphalt shingle roof systems because doing so may damage the shingles. However, typical application instructions require the roof surface to be clean and dry before application to ensure the coating properly adheres. It is also possible that the roofs were not given adequate time to fully dry out. The coating, forming one continuous water proof layer, may have trapped moisture into the roofing assembly. As stated previously, asphalt shingles are small units that are designed to shed water, not to be water proof.

Only one respondent reported experiencing roof storm damage since the application of the coating.

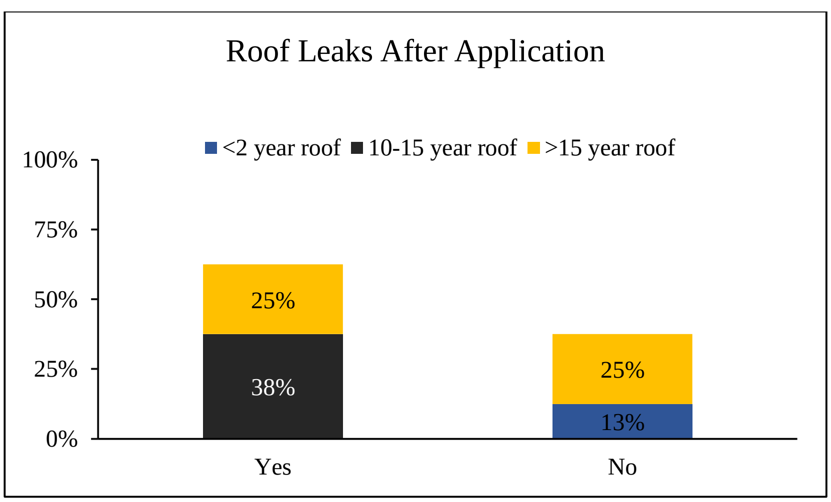

Figure 15: Roof leaks percentage distribution with respect to age of roof.

4.1.5 Roof coating appearance and overall satisfaction

One of the survey questions asked occupants about the appearance of the coatings to see if they noticed any signs of fading, discoloration, peeling or cracking since application. Among the respondents, 75% stated that the coating appeared to be in good condition while 25% of occupants were unsure of its condition. All of the occupants stated they were satisfied overall with the application of the cool color coating.

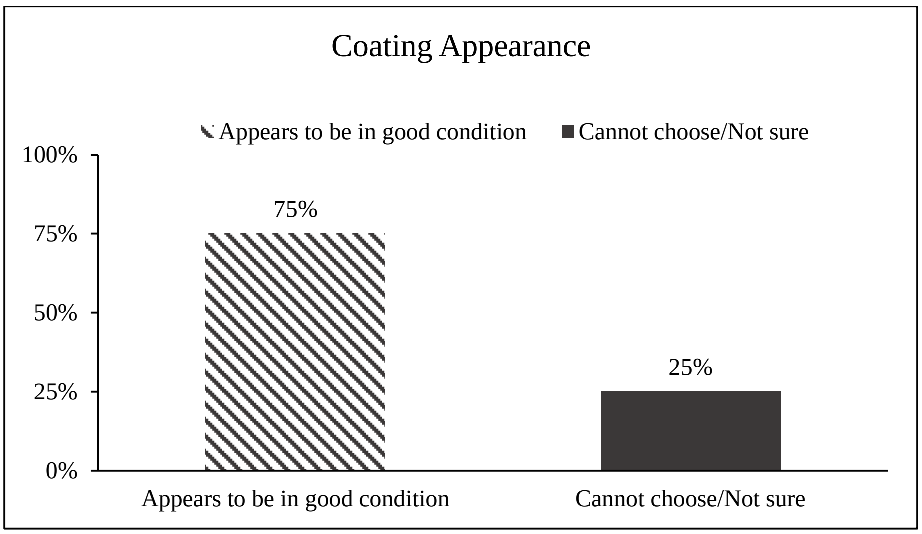

Figure 16: Coating Appearance percentage distribution of replies.

4.2 Field-Experiment Results

During the monitoring period, ambient temperatures in Albany ranged from a low of 61°F to a high of 79°F. Cloud coverage was mostly few (0/8 to 2/8 of sky) to scattered (3/8 to 4/8 of sky) sky cover. It rained on 7 out of the 15 days with average precipitation reaching 0.24 inches. Notably, 1.61 inches of rain fell on 4/19/2015. Relative humidity stayed fairly high with 78% being the average for the 2 week period. Local weather conditions for each day are presented in Appendix D.

4.2.1 Surface Temperatures

The Jasper NXT roof coating increased the solar reflectance of the asphalt shingles from 0.10 to 0.32. The added 22 points of solar reflectance dropped the surface temperature of the coated shingles below those of the uncoated shingles at midafternoon. Figure 16 shows temperatures obtained from the external surface of the analyzed roof modules with respect to the ambient temperature on the warmest day of the 2 week period with a high of 79°F (4/26/2014).

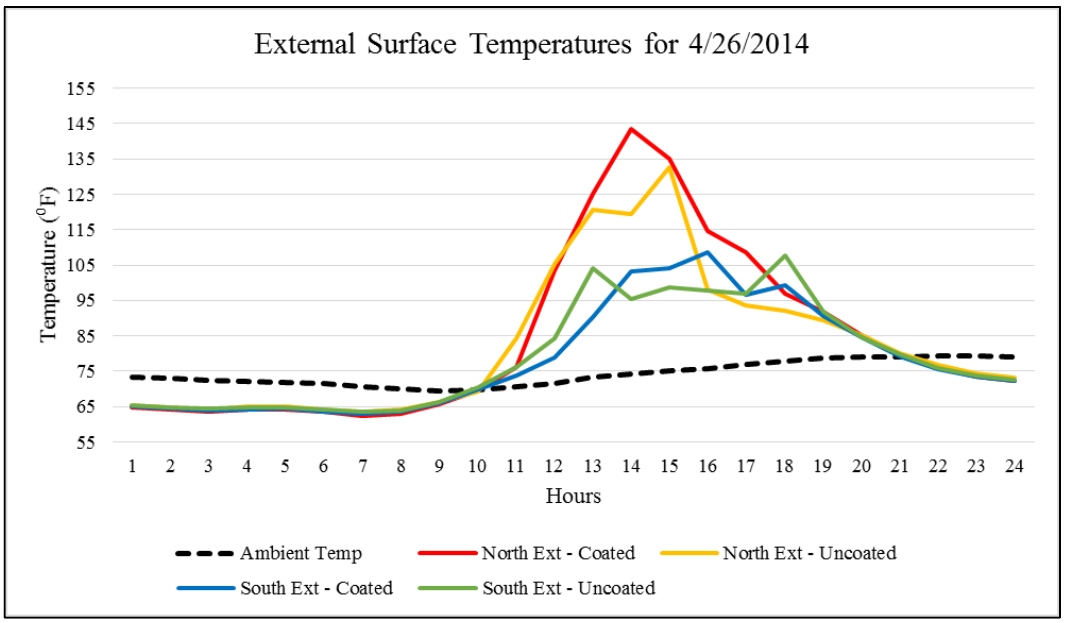

Figure 17: External surface temperatures for uncoated Module 1 and coated Module 2 with respect to the ambient temperture on April 26th.

As evident from Figure 16, the surface temperatures of both modules were significantly higher than the ambient temperature during peak sun intensity hours (10 a.m. to 2 p.m.). It was apparent that roof orientation greatly impacted the thermal behavior of the roofs. Both the coated and uncoated north-facing roof had relatively high temperature distributions when compared to the south-facing coated and uncoated roof. Surprisingly, the north-facing coated roof surface had the highest maximum temperature reading at 143.5°F. In contrast, the south-facing coated roof had the lowest temperature reading with a minimum temperature of 62.9°F. Preliminary f-tests for equality of variances indicated that the variances of the external surface temperatures were significantly different. Therefore, two-sample t-tests, assuming unequal variances, were performed to compare the means of the temperatures of roof module 1(north and south facing roofs) and module 2 (north and south facing roofs), considering the impact of time of day at 1 hour-intervals. A summary of t-test results is presented in Appendix B.

4.3 T-test Results

<u>4.3.1 External Roof Surface Temperature (North-Facing)</u>

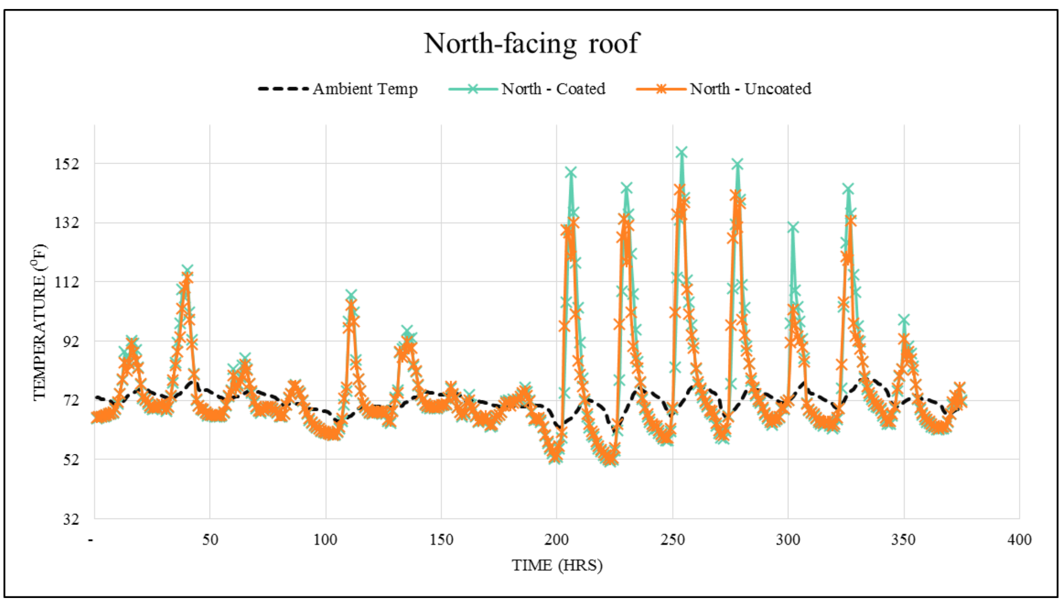

Figure 18: External surface temperature at north-facing roof.

T-test results revealed significant differences between the mean temperatures of the coated roof surface and the uncoated roof surface at the north-slope. Specifically, it was found that between the hours of 10:00 am to 11:00 am, the mean surface temperature of uncoated module 1 was 4 to 5°F warmer than the mean surface temperature for coated module 2; however, between the hours of 11:00 am to 6:00 pm, the surface temperature of the uncoated roof module was 3 to 10°F cooler than the surface temperature of the uncoated roof module. One would expect the NIR reflective coated shingles to be cooler throughout peak sun hours. This observation seems to be attributed to the shadow cast by a large tree located adjacent to the shed which reduced incident solar radiation, or the amount of radiant energy absorbed by the uncoated asphalt shingles. Figure 18 illustrates the tree locations with respect to the test shed. A shading study for April 26th, 2015, the warmest day, using Revit Sun Path is shown in Figure 19. In order to quantify the shading effects of the tree, theoretical solar insolation values for the south facing roof were calculated using the Solar Analysis tool in Revit. The results are presented in Table 3. Daily average solar insolation was 55.2 kWh/m^2 for the coated roof surface, 68% higher than the insolation value for the uncoated roof surface which was 32.80 kWh/m^2, during the monitoring period.

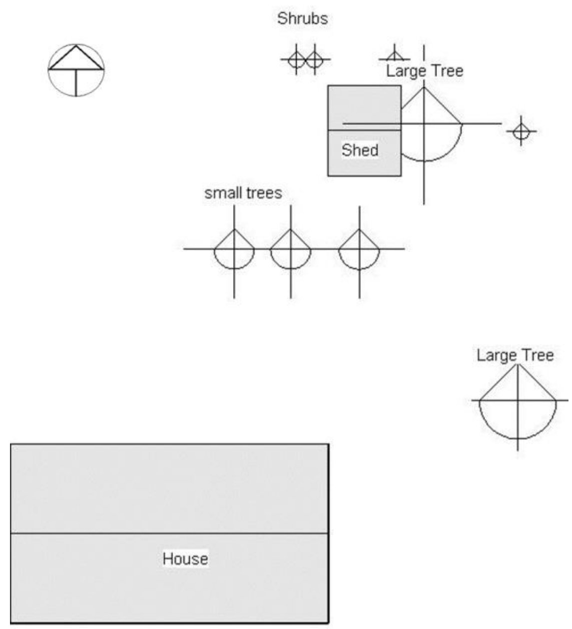

Figure 19: Tree location with respect to building.

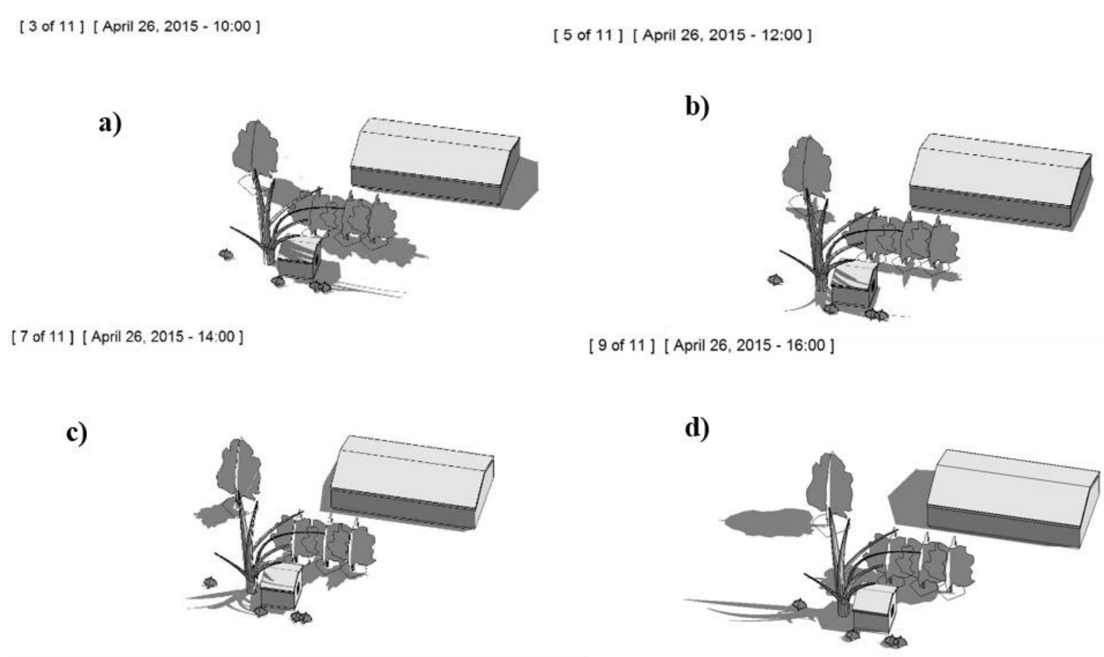

Figure 20: Theoretical shading study for April 26th, 2015, the warmest day, using Revit Sun Path. Shading cast on shed at a) 10:00 a.m., b) 12:00 p.m., c) 2:00 p.m., and d) 4:00 p.m.

4.3.2 External Roof Surface Temperature (South-Facing)

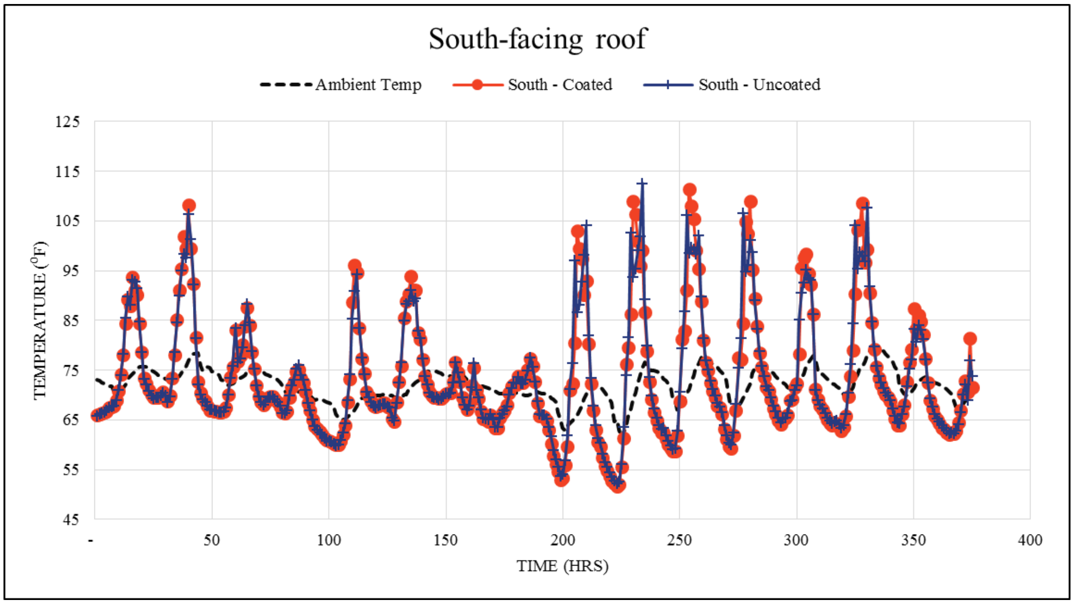

Figure 21: External surface temperature of south facing roof.

T-test results also showed significant differences between the mean temperatures of the coated and the uncoated roof surfaces facing south. Similar to the measurements of the north-facing roof, the coated south-facing roof was 2 to 5°F cooler than the uncoated surface between the hours of 12:00 pm to 1:00 pm and 5:00 pm to 6:00 pm; however, between the hours of 1:00 pm to 5:00 pm, the mean surface temperature for uncoated module one was 2 to 5°F warmer than the mean surface temperature for coated module two.

Theoretical solar insolation values for the south facing roof were also calculated using Solar Analysis tool in Revit. The results are shown in Table 3. Daily average solar insolation was 67.08 kWh/m^2 for the coated roof surface, 101% higher than the solar insolation value for the uncoated roof surface, 33.33 kWh/m^2. The Solar Analysis results suggest that shading from the tree greatly reduced the amount of incident solar radiation striking the surface of the uncoated shingles, thus keeping the surface cooler.

Table 3: Averaged daily solar insolation value for north and south facing roofs.

	Coated North Facing Roof	Uncoated North Facing Roof	Coated South Facing Roof	Uncoated South Facing Roof
Daily solar insolation value per m^2 (kWh/m^2)	55.20	32.80	67.08	33.33

4.3.3 Attic Temperatures

Results for the t-tests between the mean temperatures of the attic assembly of the coated and uncoated roof revealed no statistical significance at any 1 hour interval with p-values greater than 0.05. However, descriptive statistics show differences among the two attic spaces (Appendix C). The lack of significant temperature differences may be attributed to gaps in the thermal barrier installed between the two attic assemblies. Using a different insulation product with a higher R-value or using additional layers of EPS foam to seal the path of connection would have more effectively reduced the heat flow between the two attic spaces.

A key task was to identify the factors that affect the thermal behavior of the cool color coated roof. Statistical testing for correlation between coated roof surface temperature and external conditions including ambient temperature, sky conditions, visibility, dew point temperature, relative humidity, solar altitude and azimuth angle were performed. Test results represented in Figure 21 showed that relative humidity was negatively correlated with coated roof surface temperature, while solar altitude angle was positively correlated with coated roof surface temperature (i.e.,$R = 0.432, p < 0.01; R =$

$0.426, p < 0.01$, respectively.) Statistical tests for correlation between sky conditions, visibility, dew point temperature, and solar azimuth angle did not pass the criteria at a significance level of 0.05.

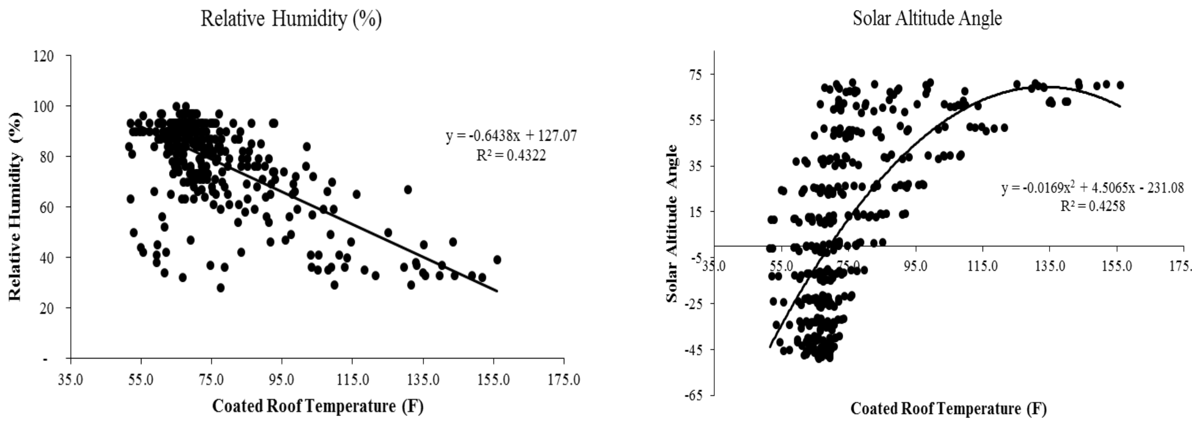

Figure 22: Relationships between coated surface temperature, relative humidity, and solar altitude angle.

4.4 Predicting surface temperatures of coated asphalt shingle roof

Multiple linear regression analysis was also used to develop two regression model for predicting the surface temperature of the north and south-facing coated asphalt shingle roofs from the ambient temperature, sky conditions, dew point temperature, relative humidity, solar altitude and azimuth angle. Correlations on the pairs of variables were performed to screen for significant bivariate correlation. According to Tabachnick & Fidell (1996), independent variables with a bivariate correlation more than .70 should not be included in multiple regression analysis. Basic descriptive statistics and correlations between the predictor variables are shown in Table 4.

The 6 predictor model for the south-facing roof was able to account for 75% of the variance in the hourly surface temperature ($F(6,368) = 181.20, p < .05, R^2 = .75, 95\%\ CI$. The 6 predictor model for the north-facing roof was able to account for 65% of the variance in the hourly surface temperature($F(6,368) = 134.89, p < .05, R^2 =$

$.65, 95\%\ CI$. The relationship between the predictors and roof temperature are described in the following regression equations:

$$\boxed{y_S = -21.432 + 1.336(T_a) + 0.723(SC\ nominal) + .465(T_d) - .416(RH) + .101(ALT) + .021(AZI)}$$

Equation 1: Regression equation for predicting temperature of south facing coated roof from ambient temperature ($\boldsymbol{T_a}$), sky conditions($\boldsymbol{SC\ nominal}$), dew point temperature($\boldsymbol{T_d}$), relative humidity($\boldsymbol{RH}$), solar altitude($\boldsymbol{ALT}$), and azimuth angle($\boldsymbol{AZI}$)

$$\boxed{y_N = 7.963 + 1.222(T_a) + 0.925(SC\ nominal) + .542(T_d) - .722(RH\%) + .121(ALT) + .021(AZI)}$$

Equation 2: Regression equation for predicting temperature of north facing coated roof from ambient temperature ($\boldsymbol{T_a}$), sky conditions($\boldsymbol{SC\ nominal}$), dew point temperature($\boldsymbol{T_d}$), relative humidity($\boldsymbol{RH}$), solar altitude($\boldsymbol{ALT}$), and azimuth angle($\boldsymbol{AZI}$)

Table 4: Correlations between Predictor Variables

Variable	Azimuth Angle	Altitude Angle	Relative Humidity	Dew Point Temp	Ambient Temp
Sky Cond.	-0.180	0.070	0.385	0.437	-0.127
Ambient Temp	0.295	-0.259	0.206	0.429	
Dew Point Temp	0.063	-0.073	0.641		
Relative Humidity	-0.119	-0.565			
Altitude Angle	0.214				
Azimuth Angle					
Mean	-18.21	8.37	78.05	61.77	71.95
SD	106.15	39.16	18.03	6.99	3.28

RECOMMENDATIONS FOR FUTURE RESEARCH

While this study provides a good start to understanding near-infrared reflective coatings used on asphalt shingles, the reliability of the results are limited by the small sample size and the short monitoring period for the field experiment. Further field-studies are necessary to generalize and validate the findings. One recommendation for future research is to conduct periodic or ongoing occupant thermal comfort and perception surveys while simultaneously measuring the physical variables of the interior and exterior environment. This would provide a more precise comparison between occupant perceptions and actual conditions. The surveys should be conducted pre- and post-application of the coating. The field results in this study are limited to conditions during the spring season, specific to the climate conditions of Albany, Georgia. Another experiment needs to be conducted monitoring the roof's thermal behavior during the summer, as well as throughout the entire year to fully access their performance. Additionally, testing different cool colors and/or brands of NIR reflective coatings may yield different results.

CONCLUSION

The purpose of this exploratory study was to present a process that can be used to evaluate the perceived and actual benefits of NIR coatings field-applied to asphalt shingles on single-family houses. Using questionnaires, the study attempted to evaluate occupants perceived benefits in regards to indoor air quality, noise, energy costs, and occupant satisfaction. Objective data was collected by conducting a field experiment on a on a single-room, unoccupied, unconditioned shed in Albany, Georgia. The roof of the shed was divided into two roofing assemblies of the same size, on the south and north facing roofs. This was done to compare the performance of a NIR reflective coated asphalt shingle roof system with that of a conventional asphalt shingle roof system.

Questionnaire results showed that occupants did not perceive any significant changes to their indoor environment but were satisfied overall with the application and appearance of the roof coating. It was also found that 63% of the occupants experienced some form of roof leak following application of the coating. This provides anecdotal evidence that coatings should not be field-applied to installed asphalt shingle roofs, especially roofs that are 10 years or older that are in need of replacement.

Field-results showed that the field-coated roof surface was 2 to 5°F cooler than the uncoated roof surface at midafternoon; however, further into peak sun hours, the coated roof was 2 to 10°F warmer than the uncoated roof surface. This surprising observation is likely attributed to shading from neighboring objects which was not taken in consideration during building selection. To analyze the impact of shading, we used the Solar Analysis tool in Revit to calculate daily average solar insolation values for the uncoated and coated roof surfaces during the 2 week period. The results indicated that daily average solar insolation values for the uncoated roof surface was about 68-101% lower than the insolation value of the coated roof surface, as result of surrounding obstacles. Statistical testing for correlation between coated roof surface temperature and external conditions revealed that relative humidity was negatively correlated with coated roof surface temperature, while solar altitude angle was positively correlated with coated roof surface temperature (i.e.,$R = 0.432, p < 0.01; R = 0.426, p < 0.01$, respectively.) Multiple linear regression analysis was used to develop a model for predicting the surface temperature of the coated asphalt shingle roofs (north and south facing) from the ambient temperature, sky conditions, dew point temperature, relative humidity, solar altitude and azimuth angle. The 6 predictor model was able to account for 75% of the variance in the hourly temperature of the south-facing coated roof, roof ($F(6,368) = 181.20, p < .05, R^2 = .75, 95\%\ CI$ and 65% of the variance in the hourly temperature of the north-facing coated roof($F(6,368) = 134.89, p < .05, R^2 = .65, 95\%\ CI$.

APPENDIX A: SURVEY INSTRUMENT

Questionnaire

1. **How many years have you lived in the home?**
    1. ☐ Less than 2 years
    2. ☐ 3 to 5 years
    3. ☐ 6 to 10 years
    4. ☐ More than 10 years
    5. ☐ Cannot choose/Not sure
2. **How many bedrooms does your house have?**
    1. ☐ None
    2. ☐ 1
    3. ☐ 2
    4. ☐ 3
    5. ☐ 4 or more
3. **How many bathrooms does your house have?**
    1. ☐ None
    2. ☐ 1
    3. ☐ 1-1/2
    4. ☐ 2 or more
4. **How many floors does your house have?**
    1. ☐ 1 floor
    2. ☐ 2 floors
    3. ☐ 3 floors
    4. ☐ More than 3 floors
5. **What is the size of your home? If you know the size, please state it: ________________. If you do not know the size of your home, please select one the following ranges:**
    1. ☐ Less than 749
    2. ☐ 750 to 999
    3. ☐ 1000 to 1,499
    4. ☐ 1,500 to 1,999
    5. ☐ 2,000 to 2,499
    6. ☐ 2,500 to 2,999
    7. ☐ 3,000 to 3,999
    8. ☐ 4,000 or more
    9. ☐ Cannot choose/Not sure
6. **What type of roof does your house have?**
    1. ☐ Asphalt shingles
    2. ☐ Metal
    3. ☐ Clay or Concrete Tiles
    4. ☐ Slate Shingles
    5. ☐ Wood shingles
    6. ☐ Fiber Cement
    7. ☐ Other ________________ (If other, please state)
    8. ☐Cannot choose/Not sure
7. **What is the age of your roof?**
    1. ☐ Less than 2 years
    2. ☐ 3 to 5 years
    3. ☐ 6 to 10 years
    4. ☐ 10 to 15 years
    5. ☐ More than 15 years
    6. ☐ Cannot choose/Not sure

8. **How long ago did your roof receive a coating?**
    1. ☐ Less than 6 months
    2. ☐ 1-2 years
    3. ☐ 3-4 years
    4. ☐ 5-6 years
    5. ☐ 7-8 years
    6. ☐ 9-10 years
    7. ☐ 11 or more years
    8. ☐ Cannot choose/Not sure
9. **What type of coating was applied to the roof? If you know the type, please state:**
    1. ___________________
    2. ☐ Not sure
10. **Was a white, other light color or dark colored coating applied to your roof?**
    1. ☐ White
    2. ☐ Other Light color
    3. ☐ Dark color
    4. ☐ Cannot choose/Not sure
11. **After the application of the roof coating, have you experienced any roof leaks?**
    1. ☐ Yes
    2. ☐ No
12. **After the application of the roof coating, have you experienced any storm damage to the roof?**
    1. ☐ Yes
    2. ☐ No

13. **After the application of the roof coating, the amount of noise I can hear from the outside has:**

1. Significantly Increased	2. Increased	3. Somewhat Increased	4. Not Changed	5. Somewhat Decreased	6. Decreased	7. Decreased Significantly
☐	☐	☐	☐	☐	☐	☐

14. **After the application of the roof coating, my energy costs have:**

1. Significantly Increased	2. Increased	3. Somewhat Increased	4. Not Changed	5. Somewhat Decreased	6. Decreased	7. Decreased Significantly
☐	☐	☐	☐	☐	☐	☐

15. **How cool do you keep your home in the summer?**
    1. ☐ 68°F or lower
    2. ☐69
    3. ☐ 70
    4. ☐ 72
    5. ☐ 73
    6. ☐ 74
    7. ☐ 75
    8. ☐ 76
    9. ☐ 77
    10. ☐ 78
    11. ☐ 79
    12. ☐ 80°F or higher
16. **What temperature do you keep your house at during winter?**

1. ☐ 68°F or lower
2. ☐69
3. ☐ 70
4. ☐ 72
5. ☐ 73
6. ☐ 74
7. ☐ 75
8. ☐ 76
9. ☐ 77
10. ☐ 78
11. ☐ 79
12. ☐ 80°F or higher

17. Are the walls of the house insulated? If so, what type of insulation was used?

1. ☐ Blanket: batts and rolls
2. ☐ Concrete block insulation
3. ☐ Foam board or rigid foam
4. ☐ Loose-fill and blown in
5. ☐ Sprayed foam
6. ☐ Other _______________ (If other, please state)
7. ☐ Not insulated
8. ☐ Cannot choose/Not sure

18. Is the attic of the house insulated? If so, what type of insulation was used?

1. ☐ Blanket: batts and rolls
2. ☐ Concrete block insulation
3. ☐ Foam board or rigid foam
4. ☐ Loose-fill and blown in
5. ☐ Sprayed foam
6. ☐ Other _______________ (If other, please state)
7. ☐ Not insulated
8. ☐ Cannot choose/Not sure

19. Are the floors of the house insulated? If so, what type of insulation was used?

1. ☐ Blanket: batts and rolls
2. ☐ Concrete block insulation
3. ☐ Foam board or rigid foam
4. ☐ Loose-fill and blown in
5. ☐ Sprayed foam
6. ☐ Other _______________ (If other, please state)
7. ☐ Not insulated
8. ☐ Cannot choose/Not sure

20. After the application of the roof coating, the air inside the house is:

1. ☐ Air is stuffy
2. ☐ Air is stale
3. ☐ Air is humid
4. ☐ Air has an odor
5. ☐ Not changed
6. ☐ Cannot choose/Not sure

21. What type of cooling system do you have in the home?

1. ☐ Window Air Conditioner
2. ☐ Central Air Conditioner
3. ☐ Portable Air Conditioner
4. ☐ Other ________________ (If other, please state)
5. ☐ Cannot choose/Not sure

22. If central, are the air ducts located in the attic of your home?

1. ☐Yes
2. ☐ No
3. ☐ Cannot choose/Not sure

23. After the application of the roof coating, cooling the home (for example, from 79 degrees to 74 degrees Fahrenheit) takes:

1. ☐ Shorter than 5 minutes
2. ☐ 5 to 10 minutes
3. ☐ 11 to 15 minutes
4. ☐ 16 -20 minutes
5. ☐ 20 to 25 minutes
6. ☐ 26 to 30 minutes
7. ☐ Over 30 minutes
8. ☐ Cannot choose/Not sure

24. In regards to the appearance of the roof coating, have you noticed any of the following (check all that apply):

1. ☐ Color or hue uneven or fading
2. ☐ Cracking
3. ☐ Erosion or deterioration
4. ☐ Peeling
5. ☐ Flaking
6. ☐ Appears to be in good condition
7. ☐ Cannot choose/Not sure

25. Has the roof of the house received a reapplication of the roof coating?

1. ☐ Yes
2. ☐ No
3. ☐ Cannot choose/Not sure

26. How satisfied are you overall with the application of the roof coating?

1. Very Satisfied	**2. Satisfied**	**3. Somewhat Satisfied**	**4. Neutral**	**5. Somewhat Dissatisfied**	**6. Dissatisfied**	**7. Very Dissatisfied**
☐	☐	☐	☐	☐	☐	☐

Thank you for your cooperation in completing this survey. Please email completed survey to: cpowers7@gatech.edu

APPENDIX B: T-TEST RESULTS

Table 5: Attic T-Test

	Attic T-test Results					
1 hr-Interval	m1 (uncoated)	m2 (coated)	Diff. (ºF)	T-stat	P-value	DF
12:00 AM to 1:00:00 AM	71.43	70.85	-0.57	1.80	0.07	414
1:00 AM to 2:00:00 AM	70.55	70.00	-0.55	1.79	0.07	414
2:00 AM to 3:00:00 AM	69.78	69.23	-0.55	1.79	0.07	414
3:00 AM to 4:00:00 AM	69.07	68.54	-0.53	1.70	0.09	414
4:00 AM to 5:00:00 AM	68.51	67.99	-0.52	1.61	0.11	414
5:00 AM to 6:00:00 AM	67.97	67.43	-0.54	1.59	0.11	414
6:00 AM to 7:00:00 AM	67.41	66.91	-0.50	1.41	0.16	414
7:00 AM to 8:00:00 AM	66.86	66.38	-0.48	1.31	0.19	414
8:00 AM to 9:00:00 AM	66.80	66.36	-0.44	1.15	0.25	414
9:00 AM to 10:00:00 AM	67.35	67.00	-0.35	0.89	0.38	414
10:00 AM to 11:00:00 AM	68.53	68.34	-0.19	0.48	0.63	414
11:00 AM to 12:00:00 PM	70.61	70.60	-0.01	0.03	0.98	414
12:00 PM to 1:00:00 PM	73.54	73.76	0.23	-0.54	0.59	413
1:00 PM to 2:00:00 PM	76.89	77.68	0.79	-1.40	0.16	410
2:00 PM to 3:00:00 PM	78.20	79.32	1.11	-1.81	0.07	384
3:00 PM to 4:00:00 PM	79.66	80.13	0.48	-0.72	0.47	387
4:00 PM to 5:00:00 PM	80.50	80.98	0.48	-0.71	0.48	387
5:00 PM to 6:00:00 PM	80.49	80.72	0.23	-0.36	0.72	388
6:00 PM to 7:00:00 PM	79.88	79.87	-0.01	0.02	0.98	388
7:00 PM to 8:00:00 PM	78.22	77.97	-0.25	0.48	0.63	388
8:00 PM to 9:00:00 PM	76.59	76.14	-0.45	0.97	0.34	388
9:00 PM to 10:00:00 PM	74.98	74.43	-0.55	1.28	0.20	388
10:00 PM to 11:00:00 PM	73.61	73.03	-0.58	1.49	0.14	388
11:00 PM to 12:00:00 AM	72.52	71.93	-0.59	1.56	0.12	358

Table 6: North-facing Roof T-Test

	North-facing Roof T-Test Results					
1 hr-Interval	**m1 (uncoated)**	**m2 (coated)**	**Diff. (ºF)**	**T-stat**	**Pvalue**	**DF**
12:00 AM to 1:00:00 AM	66.81	66.21	(0.60)	1.81	0.07	414
1:00 AM to 2:00:00 AM	66.10	65.55	(0.55)	1.52	0.13	414
2:00 AM to 3:00:00 AM	65.54	64.98	(0.55)	1.38	0.17	414
3:00 AM to 4:00:00 AM	65.08	64.56	(0.52)	1.17	0.24	413
4:00 AM to 5:00:00 AM	64.60	64.08	(0.51)	1.09	0.27	414
5:00 AM to 6:00:00 AM	64.20	63.69	(0.51)	1.02	0.31	414
6:00 AM to 7:00:00 AM	63.60	63.08	(0.52)	1.00	0.32	414
7:00 AM to 8:00:00 AM	64.01	63.45	(0.56)	1.07	0.28	414
8:00 AM to 9:00:00 AM	66.33	65.87	(0.46)	0.89	0.38	413
9:00 AM to 10:00:00 AM	69.67	69.28	(0.38)	0.77	0.44	411
10:00 AM to 11:00:00 AM	81.27	75.45	(5.81)	4.67	0.00	277
11:00 AM to 12:00:00 PM	92.63	87.76	(4.87)	2.31	0.02	382
12:00 PM to 1:00:00 PM	96.30	97.43	1.13	(0.44)	0.66	414
1:00 PM to 2:00:00 PM	98.10	108.23	10.13	(3.66)	0.00	383
2:00 PM to 3:00:00 PM	101.83	104.23	2.40	(0.88)	0.38	390
3:00 PM to 4:00:00 PM	91.86	98.35	6.49	(4.03)	0.00	356
4:00 PM to 5:00:00 PM	87.05	92.65	5.61	(5.04)	0.00	337
5:00 PM to 6:00:00 PM	83.55	86.27	2.72	(3.38)	0.00	367
6:00 PM to 7:00:00 PM	79.59	80.32	0.73	(1.10)	0.27	385
7:00 PM to 8:00:00 PM	74.76	74.50	(0.26)	0.52	0.61	388
8:00 PM to 9:00:00 PM	71.53	71.02	(0.51)	1.21	0.23	388
9:00 PM to 10:00:00 PM	69.62	69.06	(0.55)	1.38	0.17	388
10:00 PM to 11:00:00 PM	68.42	67.82	(0.59)	1.65	0.10	388
11:00 PM to 12:00:00 AM	67.65	67.04	(0.61)	1.75	0.08	358

Table 7: South-facing T-Test

	South-facing Roof T-Test Results					
1 hr-Interval	m1 (uncoated)	m2 (coated)	Diff.	T-stat	P-value	DF
12:00 AM to 1:00:00 AM	66.52	66.28	-0.2	0.71	0.48	414
1:00 AM to 2:00:00 AM	65.90	65.63	-0.3	0.75	0.45	413
2:00 AM to 3:00:00 AM	65.40	65.11	-0.3	0.74	0.46	412
3:00 AM to 4:00:00 AM	64.88	64.62	-0.3	0.61	0.54	412
4:00 AM to 5:00:00 AM	64.37	64.12	-0.3	0.56	0.57	413
5:00 AM to 6:00:00 AM	63.98	63.74	-0.2	0.49	0.63	413
6:00 AM to 7:00:00 AM	63.39	63.16	-0.2	0.46	0.64	413
7:00 AM to 8:00:00 AM	63.70	63.49	-0.2	0.41	0.68	413
8:00 AM to 9:00:00 AM	66.02	65.86	-0.2	0.32	0.46	413
9:00 AM to 10:00:00 AM	69.60	69.40	-0.2	0.39	0.70	405
10:00 AM to 11:00:00 AM	74.08	74.17	0.1	(0.18)	0.86	412
11:00 AM to 12:00:00 PM	78.66	77.39	-1.3	1.89	0.06	409
12:00 PM to 1:00:00 PM	86.56	81.25	-5.30	4.50	0.00	332
1:00 PM to 2:00:00 PM	85.84	91.32	5.48	-4.45	0.00	352
2:00 PM to 3:00:00 PM	87.69	91.54	3.84	-3.13	0.00	370
3:00 PM to 4:00:00 PM	90.07	92.57	2.50	-1.95	0.05	376
4:00 PM to 5:00:00 PM	89.67	88.57	-1.1	1.09	0.27	383
5:00 PM to 6:00:00 PM	89.21	86.48	-2.74	2.52	0.01	351
6:00 PM to 7:00:00 PM	80.76	80.33	-0.4	0.61	0.54	386
7:00 PM to 8:00:00 PM	74.84	74.62	-0.2	0.43	0.67	388
8:00 PM to 9:00:00 PM	71.34	71.14	-0.2	0.49	0.63	388
9:00 PM to 10:00:00 PM	69.33	69.15	-0.2	0.48	0.63	388
10:00 PM to 11:00:00 PM	68.05	67.84	-0.2	0.59	0.55	388
11:00 PM to 12:00:00 AM	67.26	67.04	-0.2	0.64	0.52	358

APPENDIX C: DESCRIPTIVE STATISTICS

Table 8: Descriptive Statistics

	Attic - Uncoated	Attic - Coated	North facing roof - Uncoated	North facing roof - Coated	South facing roof - Uncoated	South facing roof - Coated
Mean	72.79	72.61	75.74	76.14	73.49	73.38
Standard Error	0.10	0.10	0.26	0.28	0.18	0.18
Median	71.60	71.20	70.00	69.60	69.80	69.80
Mode	69.60	68.50	69.60	69.60	69.62	69.62
Standard Deviation	6.47	6.81	17.22	18.81	11.85	12.21
Sample Variance	41.86	46.37	296.42	353.90	140.52	149.10
Kurtosis	-0.04	-0.01	5.41	4.79	1.16	1.50
Skewness	0.51	0.57	2.19	2.12	1.16	1.23
Range	31.50	32.90	108.00	110.00	73.98	75.06
Minimum	57.90	57.20	51.80	51.10	51.98	51.26
Maximum	89.40	90.10	159.80	161.10	125.96	126.32
Sum	326762.70	325929.60	339993.50	341789.10	329910.56	329415.74
Count	4489.00	4489.00	4489.00	4489.00	4489.00	4489.00

APPENDIX D: DAILY CLIMATE CONDITIONS

Table 9: Daily Climate Conditions

Date	Temp High	Temp Low	Temp Average	Precipitation (inches)	Humidity Average	Pressure High	Pressure Low
4/13/2015	75.7	70.7	73.2	0.15	87%	30.21	30.09
4/14/2015	78.4	72.5	75.1	0.11	87%	30.16	30.04
4/15/2015	75.4	72	73.9	0.31	88%	30.15	30.03
4/16/2015	74.3	68.7	71.3	0	85%	30.23	30.12
4/17/2015	69.8	64.9	67.9	0.13	85%	30.19	29.98
4/18/2015	74.8	69.4	71.4	0.6	89%	30.03	29.94
4/19/2015	74.8	71.2	73	1.61	89%	29.98	29.81
4/20/2015	71.1	69.6	70.3	0	89%	29.92	29.8
4/21/2015	72.1	62.4	67.8	0	76%	30.09	29.91
4/22/2015	76.6	61.3	69.9	0	67%	30.08	29.95
4/23/2015	77.5	66.9	72.8	0	69%	30.01	29.94
4/24/2015	76.1	66.6	72.6	0	62%	30.11	29.95
4/25/2015	78.1	71.1	73.8	0.65	77%	29.96	29.69
4/26/2015	79.3	69.3	74.6	0	78%	29.79	29.69
4/27/2015	78.8	69.8	73.3	0	71%	29.9	29.73

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